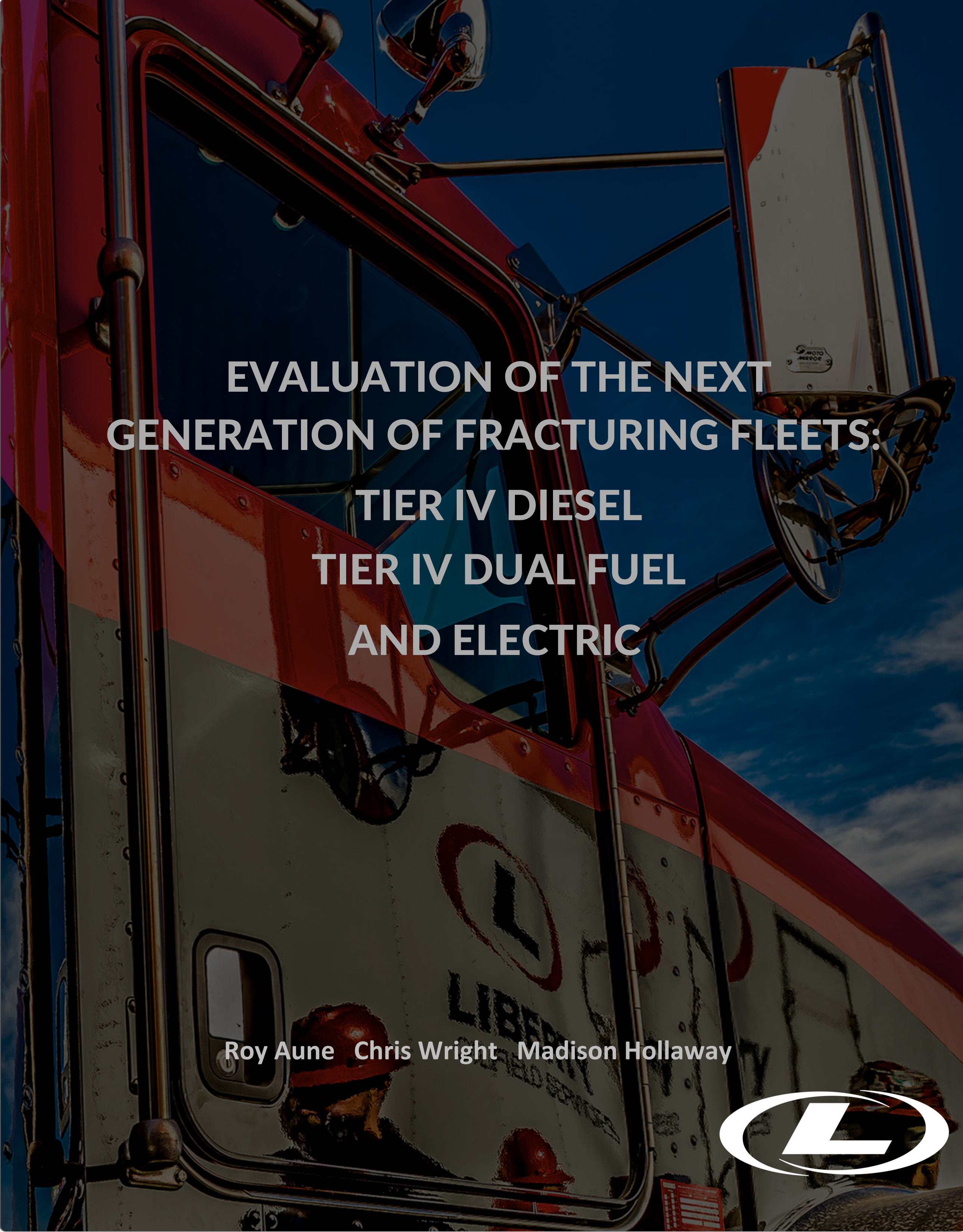

EVALUATION OF THE NEXT GENERATION OF FRACTURING FLEETS:

TIER IV DIESEL
TIER IV DUAL FUEL
AND ELECTRIC

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Preface

The shale revolution has transformed world energy markets. The surge in US oil and gas production has pushed global oil and gas prices down so that world energy consumers save over a trillion dollars per year, helping drive up living standards globally particularly for lower income homes. Roughly 130,000 folks every day are rising out of extreme poverty (living on less than $2 per day). The recent transformation of US electric power production from coal dominated to natural gas dominated has been the largest factor in the US leading all other nations in reducing greenhouse gas (GHG) emissions. US per capita greenhouse gas emissions are at a sixty-year low! US LNG exports, together with Australia and Qatar, are helping drive a similar shift to natural gas in the global electric power sector that is still coal dominant. Natural gas has also enabled the rise of renewable electric power generation.

While the benefits of the shale revolution are manifest, nothing comes for free. Nothing is without impacts. Liberty and our whole industry work tirelessly to reduce the impacts of oil and gas production locally and globally. Liberty has developed extremely quiet fracturing fleets to mitigate the impacts when shale development is in towns or cities. We have switched to containerized sand across all our fleets to remove dust and noise from pneumatic blowers. Sophisticated routing technologies reduce truck traffic. Our drive to increase efficiency of operations has more than halved the time that it takes to complete a well pad. These are just a few of the mitigations for local communities.

This paper analyzes a parallel shift towards natural gas' growing role in powering hydraulic fracturing fleets. In the electric power sector, the rise of natural gas has been displacing coal. In the frac fleet world, natural gas is displacing diesel either through dual fuel engine technology or via natural gas turbine powered electric frac fleets. This shift provides significant environmental and economic benefits.

Introduction

Air emissions from frac fleets is the central subject of this paper. We focus on the most significant local pollutants, Oxides of Nitrogen (NOx), Carbon Monoxide (CO), and Volatile Organic Compounds (VOC's). Fortunately Sulfur Oxides (SOx) are no longer produced in meaningful quantities with diesel engines. Globally, we will focus on greenhouse gas (GHG) emissions. This paper explores the costs, emissions profiles, and provides a basis for understanding the differences between the three next generation technologies for frac fleets: Tier IV diesel engines, Tier IV dual fuel (Dynamic Gas Blending (DGB)) engines, and gas turbine powered electric frac fleets.

Virtually all electric frac fleets in the field today are driven by power dense gas turbine engines that can produce 30+ megawatts (MW) to supply a roughly 15-20 MW demand on a frac pad. In most basins considered for this paper the electrical grid is not robust enough to supply this kind of power. In the areas that have a robust grid, the challenge of coordinating a very large transient load with the utility and the high cost of the infrastructure required makes this solution, potentially, a niche application. It has also been suggested that excess energy generated by these turbines could be fed onto the grid but the same limitations that make delivery of these loads to the pad problematic also make intermittent distribution from most basins problematic. Therefore, in this paper we are not considering grid power and we assume that electric fleets will be gas turbine powered. We will update our analysis when / if new approaches arise.

From a pressure pumping standpoint, the technologies are similar, so the "best" solution depends on other factors. For the most part the decision boils down to the three E's: Emissions, Economics, and Efficiency. Each of these factors will differ based on the basin of operation and technology employed. Because of this, case studies were performed for many of the large shale plays across the US, with an emphasis on the Permian and Williston Basins. Typical frac designs, altitudes, temperatures, pressures and flow rates were used to run models for emissions and fuel consumption to compare Tier IV diesel, Tier IV dual fuel and electric frac fleets (e-fleets). On the emissions front we compared Carbon Dioxide Equivalent (CO_2e), Nitrogen Oxides (NO_x), Carbon Monoxide (CO) and Volatile Organic Compounds (VOC's). Twenty years ago, it was not uncommon to have 5,000 parts per million (ppm) of Sulphur in diesel fuel. Today the average Sulphur content for both on-road and non-road diesel is below 15 ppm. This greater than 99% reduction in Sulphur content of the fuel has effectively reduced Sulphur Dioxide (SO_2) emissions from diesel engines to zero. Therefore, SO_2 emissions are not included. VOC emissions are relatively low in gas turbines and conventional diesel engines and extremely low in today's Tier IV diesel engines.

The EPA has determined that Methane has a 25X CO_2 multiplier for its greenhouse gas impact. In other words, for this study each gram of Methane emitted will be considered the equivalent of 25 grams of CO_2. The combined Methane converted to Carbon Dioxide emissions plus Carbon Dioxide emissions is what constitutes CO_2e, or greenhouse gas emissions (GHG's). This paper will compare turbine powered electric fleets (e-fleets) and Tier IV dual fuel fleets to Tier IV diesel fleets based on emissions, economics and efficiency in the considered basins. In addition, there will be discussions to address key concepts in implementing the new fleets, including fuel considerations, redundancies and manpower.

Scientifically accurate measurements of load, fuel burn, emissions, etc. can't be achieved in the field. Reliable results require a lab environment where the variables can be tightly controlled. Engine manufacturers create computer models that predict performance based on thousands of hours of lab testing. The cases discussed in this study were provided to the engine manufacturers who ran the simulations and provided the emissions data reported in this paper.

One key concept to address with both dual fuel and e-fleets is that they both introduce the ability to utilize field gas at well-sites that might otherwise be flared. This effectively reduces the emissions of the overall system if field gas is being used. Turning flare gas to a local beneficial use has significant environmental benefits and will likely be a major driver of substituting natural gas for diesel in powering frac fleets going forward, either via dual fuel engines or electric frac fleets.

Results Summary

When analyzing the Tier IV diesel/dual fuel and e-fleets, it is necessary to examine the power conversion thermal efficiencies of each system because they drive emission profiles. E-fleets, and more specifically the gas turbines, are sensitive to anything that changes the mass flow or the density of the air at the intake of the compressor. Factors that have a significant effect are ambient air temperature, altitude, idling and load profile of the turbine. Diesel engines mitigate changes in air density with turbochargers, so their operating efficiencies are largely unaffected by any of these variables.

The efficiency of the system will have an impact on the emissions profile of the different fleets given typical operating conditions. Overall, e-fleets have higher greenhouse gas (CO_2e) and Carbon Monoxide (CO) emissions than dual fuel fleets. Conversely, while both technologies have extremely low Nitrogen Oxide emissions, diesel/dual fuel fleets will have higher NO_x emissions than e-fleets. In a Permian case study, for example, Tier IV dual fuel fleets resulted in 99% less CO emissions and 42.9% less CO_2e emissions compared to DLE turbine powered e-fleets. However, in the same study, dry Low Emission (DLE) turbines resulted in 77.8% less NO_x emissions compared to dual fuel fleets.

Comparing Tier IV dual fuel engines to gas turbine powered electric fleets, dual fuel fleets provide the best return on capital due to lower initial capital investment and shorter rig up/rig down times and thus higher operational efficiency. Dual fuel fleets consume significantly less gas than turbines due to higher thermal efficiency and if gas supply is interrupted, they automatically switch to 100% diesel. Gas turbines may require an additional back up fuel supply to reduce downtime if an interruption of the primary gas supply is experienced. Operators supplying field gas to the service company should expect fuel savings for either turbine or dual fuel powered fleets when compared to a conventional diesel fleet. E-fleets are also expected to have reduced maintenance costs compared to both diesel and dual fuel fleets.

A summary of the findings can be found in **Table 1** below.

Table 1 – Summary Table

Summary Table (*Using Tier IV Diesel as Baseline*)				
Emissions				
	CO2e	**CO**	**NOx**	
Tier IV Dual Fuel	~6% lower	~60% lower	4% - 5% higher	
E-Fleet	20% to 300% higher	380x to 1800x higher	60% to 80% lower	
Economics				
	Capital Cost	**Fuel Cost (CNG/LNG)**	**Fuel Cost (Field Gas)**	**Maintenance Cost**
Tier IV Dual Fuel	~5% higher	30% to 40% lower	55% to 60% lower	Similar
E-Fleet	~50% higher	15% to 40% lower	75% to 80% lower	11% lower
Efficiency				
	Rig Up Time	**Equipment Redundancy**	**Footprint**	
Tier IV Dual Fuel	Similar	Similar	Similar	
E-Fleet	Higher	Lower	Similar	

Thermal Efficiency & Engineering Concepts

As stated previously, operational conditions will have an impact on the thermal efficiencies of both turbines and diesel/dual fuel engines. Headline efficiencies for diesel engines are given at standard conditions of 77°F and 500 feet of altitude and for turbines are usually given at ISO conditions, defined as 59°F, 60% relative humidity and ambient pressure at sea level altitude. In real life oil field operation however, the ideal condition is far from reality. In contrast to diesel and dual fuel reciprocating engines, gas turbines are much more sensitive to variations in ambient conditions.

Figure 1 shows the de-rate trend for two gas turbines running in simple cycle when exposed to changing ambient temperatures. Turbines experience this effect because ambient temperature alters the density of the air. Changes in the air density affects the mass flow into the compressor directly affecting turbine performance. Turbines will also de-rate with increasing elevations, but the impact on thermal efficiency is almost negligible. This is because altitude will affect the power output of the turbine by altering the fuel flow volume. At higher elevations, fuel flow will decrease which drives down the power output. This relationship can be seen in **Figure 2** below.

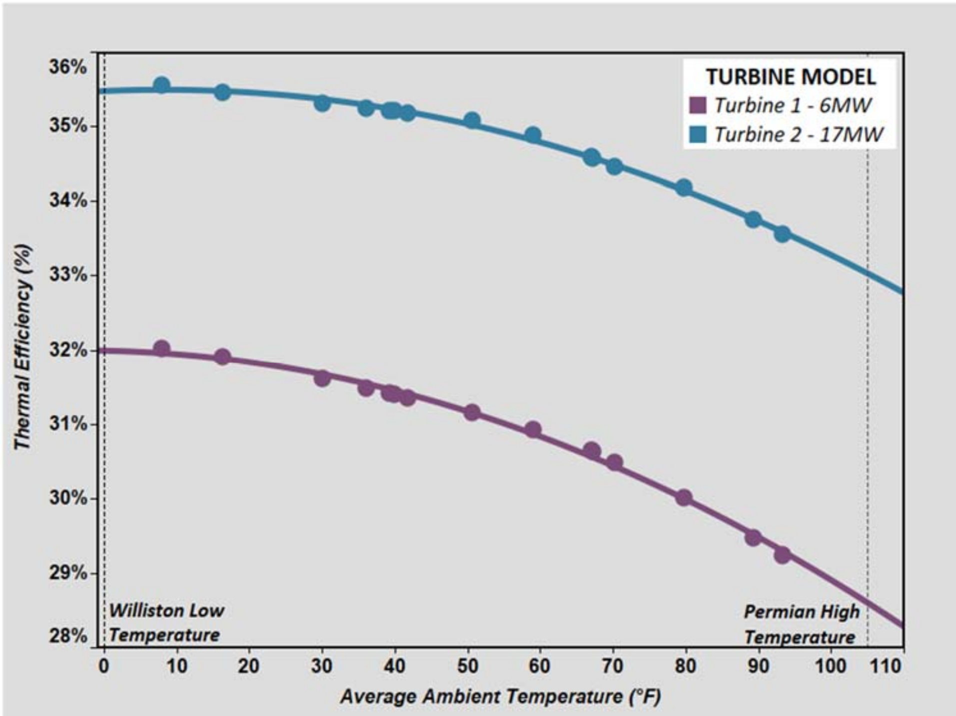

Figure 1 – Gas Turbine Thermal Efficiency vs. Ambient Temperature at 100% Load

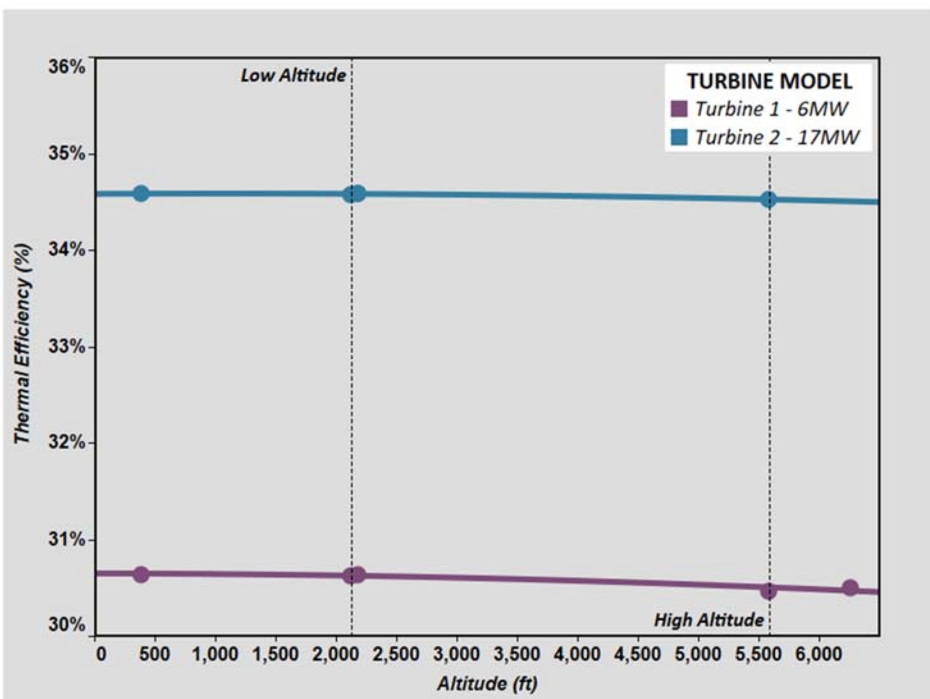

Figure 2 – Gas Turbine Thermal Efficiency vs. Altitude at 67°F & 100% Load

Gas turbines achieve optimal thermal efficiencies at 100% load. A decrease in load will result in an decrease in thermal efficiency as shown in **Figure 3.** The stars represent load points for the Permian Basin case study. Reducing the load on the turbine results in reduced fuel mass flow entering the turbine in addition to reduced compression. This lowers the temperature in the combustion chamber, resulting in less efficient combustion of the fuel. Reduced combustion efficiency results in reduced thermal efficiencies and an increase in unburned hydrocarbons, hence higher emissions.

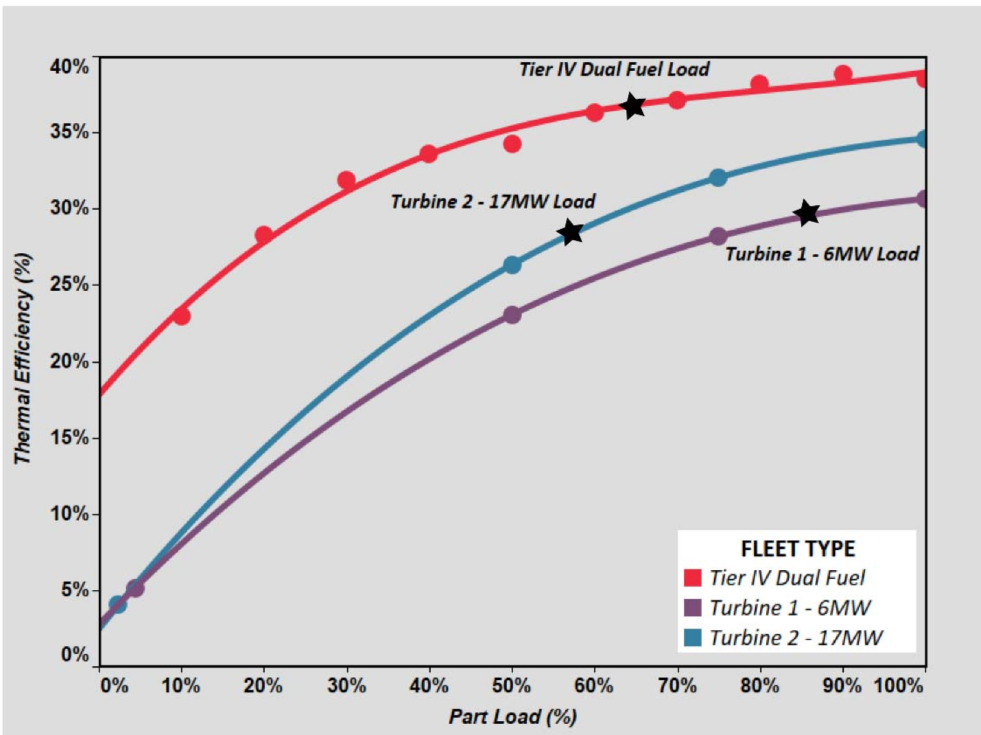

Figure 3 – Thermal Efficiency vs. Part Load De-rate Curve at 67°F

Figure 3 also shows a similar curve for dual fuel engines. Diesel engines were not included on this plot because they have an identical trend to dual fuel engines. There is, however, a unique condition with diesel and dual fuel engines. Operators have the choice to run in different gear and engine RPM combinations. Turbocharged reciprocating dual fuel and diesel engines are designed to ensure that air density and the air fuel ratio are unaffected by minor changes in ambient temperature or pressure. For dual fuel systems, the gas substitution ratios are automatically controlled to maintain efficiency based on gas quality and engine load. However, these choices have a small effect on thermal efficiency. The data points shown are an average of the minimum and maximum thermal efficiencies at each load. There can be about a ±1.5% swing in efficiency at each data point depending on engine RPM and gear. For turbines, dual fuel, and diesels alike, as the load on the engine increases, the thermal efficiency also tends to increase.

As operational conditions vary from baseline (ISO conditions), we see a disproportionate effect on turbine efficiency. To demonstrate this effect, assume this departure from ISO conditions, 60% engine load at 90°F and an altitude of 5,000 ft. Compared to ISO conditions for this case, turbine thermal efficiency will drop from 33% to 24% while the diesel/dual fuel engine will drop from 37% to 35%. ISO conditions are very rarely, if ever, achievable in oil field applications.

Analysis Methodology

This whitepaper presents the results of a technical analysis of several power system solutions for powering a hydraulic fracturing fleet. For comparison purposes, Tier IV diesel, Tier IV dual fuel, and two different turbine models powering electric fleets were evaluated at different operating points which simulate fracturing conditions in North American shale basins. Emission and economic profiles were generated, and operational impacts were considered. See **Figure 4** below for overall workflow. Sensitivities were then evaluated for each major factor such as operational efficiency, engine and turbine load profile, thermal/environmental conditions, fuel costs, natural gas quality, and availability.

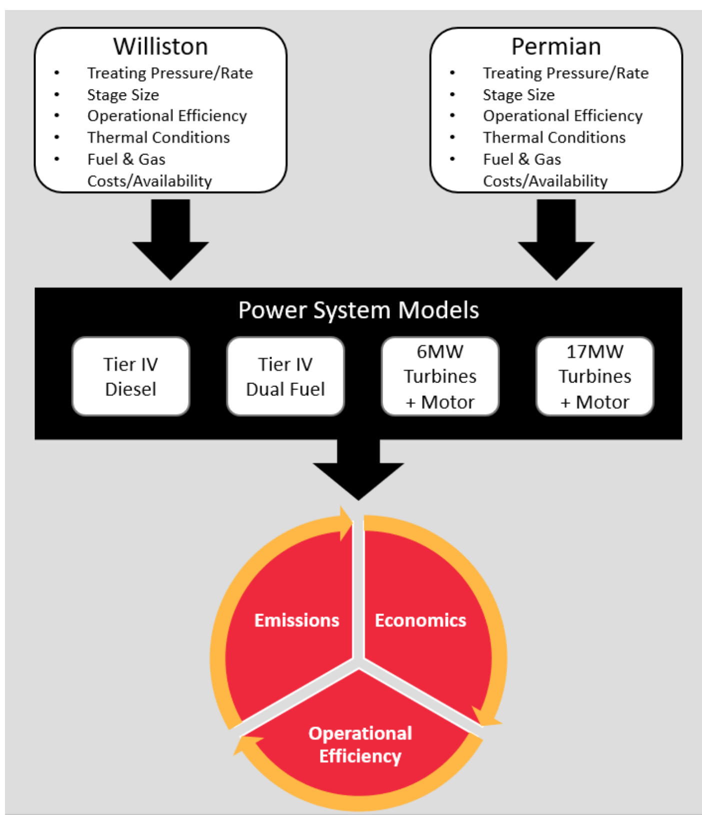

Figure 4 – General Analysis Methodology

The Permian and Williston basins were selected to evaluate baseline operational profiles. These basins were chosen to capture the widest range of environmental conditions as well as typical frac job parameters for fleet size requirements and pumping demands. For each case study, the main factors considered for modeling were ambient temperature, altitude, pumping rate, pressure, proppant amount, natural gas quality, and fluid totals. These parameters are shown in **Table 2** below for the two basins. For the models, average pressures and rates were used. Max rate and pressure were considered in order to account for the highest power demands.

Table 2 – Basin Model Parameters

	Average Temp (°F)	Average Altitude (ft)	Average Rate (bpm)	Max Rate (bpm)	Average Pressure (psi)	Max Pressure (psi)	Total Proppant per Stage (lbs)	Clean Fluid Total (bbls)	Slurry Fluid Total (bbls)	Stages per Well	Time per Stage (hrs)
Williston	67.3	2124.8	65.0	72.0	8,128	8,805	200,461	4,407	4,646	59	1.25
Permian	67.0	2180.6	93.0	100.0	8,011	9,185	452,701	10,032	10,541	55	1.78

For modeling purposes, the average temperature of each basin was used. However, it is more important to consider the full range of operating conditions from the extreme cold in the Williston basin, with temperatures sinking below 0°F, and the Permian which often has temperatures above 100°F. From the coldest operating conditions in the Williston to the hottest in the Permian, turbines will experience a 9% drop in thermal efficiency.

Daily operational efficiencies of 45%, 58% and 70% were used as the estimated data points for pump time versus non-pumping time. For example, in the 45% daily efficiency case there was an assumed 10.8 hours of pump time and 13.2 hours of non-pumping time. For all fleets it was assumed that during non-pumping time the engines and turbines were left idling. This allowed the impact of different idling behaviors between reciprocating engines and turbines to be evaluated.

Each power system was modeled from the power source to the hydraulic pump; all other equipment such as blenders, hydration units, various sand equipment, etc. were not included in the power, emissions, and fuel consumption calculations. In other words, only the turbine was considered for the e-fleet and only the engines on the frac pumps were considered for the diesel and dual fuel fleets. This simplification, however, captures the vast majority of emissions generated.

For the diesel and dual fuel fleets, the model assumed that each 2500 horsepower pump was operating at a typical engine load of ~75%. This resulted in a diesel displacement of ~70-75%, meaning that the dual fuel pumps were utilizing ~70-75% natural gas and ~25-30% diesel. These diesel displacement numbers were confirmed by Tier IV dual fuel field trials. Average rates and pressures from **Table 2** were used to determine how many pumps were operating for each case. For example, in the case of the Permian it took 13 active pumps to achieve a rate of 93 bpm if each pump was running at ~75% load. The total number of pumps per basin is shown in **Table 3** below.

Table 3 – Diesel & Dual Fuel Pump Configuration Model by Basin

	Number of Active Pumps	Active Pumping HHP Demand	Active Pumping hkW Demand
Williston	9	14,812	11,045
Permian	13	20,888	15,576

For the turbine e-fleet case the number of turbines and load on each was determined by the power required to meet the equivalent demand after de-rate, 12-17 MW in most cases. Two turbine designs were considered, Turbine Case #1 : 3-4 ~6 MW turbines and Turbine Case #2: 1-2 ~17 MW turbines. In both cases the electric motor efficiency was assumed to be 92%, which means that if the gas turbines deliver 20 MW of power to the electric motors, the motor would deliver 18.4 MW to the pump. Additional transformers and power factor reduction due to a high inductive load could cause significant further electrical losses. These additional losses can be meaningful (5%+) and are easy to measure in an operating system, but difficult to calculate. Thus, we have chosen to ignore them in this analysis. The turbine configuration for each of the case studies is show in **Table 4** below.

Table 4 – Turbine Configuration Model by Basin

		Number of Active Pumps	Load on Turbine (%)	Power per Turbine (MW)	Total Power (MW)
E-Fleet Turbine #1 - 6MW	Williston	3	81.0%	3.98	11.93
	Permian	4	85.8%	4.21	16.82
E-Fleet Turbine #2 - 17MW	Williston	1	83.0%	11.93	11.93
	Permian	2	58.6%	8.41	16.82

The models were run at multiple temperatures in each basin in order to determine how temperature will affect performance. For the case studies, however, an average temperature for each basin was used. These can be seen in **Table 2** above. Using average temperatures creates constants required for case studies, but in the worst case, high temperature applications may result in an additional turbine required to start the equipment, which could then be powered off. By contrast, dual fuel and diesel engines will not be hindered by this challenge.

Methane Number (MN) is a number that is calculated from the percentage of the constituents of the gas, ie., Methane, Ethane, Butane, etc. Methane Number is related to BTU value, but it is a better predictor of how an engine will perform burning a given gas. For both models, an 82 MN gas with a lower heating value of 939.2 BTU/scf was used. However, gas quality will have a significant effect on the emissions of gas turbines and operating parameters of dual fuel engines. For a more in-depth explanation, please refer to the "Fuel Considerations" section below.

Emissions

Since the amount of work (power supplied) was the same across all the cases being examined, emission comparisons were normalized by dividing total emissions (in grams) by the total amount of work done (in hydraulic KW-hr). **Equation 1** shows the equation used. This methodology compares the relative performance, in terms of emission efficiency, of two different technology solutions against each other without quantifying absolute totals which are subject to a large range of variables that are intentionally outside the scope of this report. In addition, this methodology allows the impact of the very different idling behaviors between traditional reciprocating engines and turbines to be quantified.

$$\frac{Emissions\ Constituent\ (grams)}{Work\ Completed\ (hkW-hr)} = Emissions\ Efficiency\ \left(\frac{grams}{hkW-hr}\right) \qquad \textbf{\textit{Equation 1}}$$

The study shows there is a trade off in emissions when it comes to dual fuel versus e-fleets. In every case tested for this paper, dual fuel had lower CO2e and CO emissions while e-fleets had lower NOx emissions. VOC's are somewhat of a special case for many reasons. There have been several papers written on the creation of VOC's and how they affect human health. Q. Lu et al. (2017) does an excellent job of explaining VOC emissions and outlining the inclusion of Semi-Volatile Organic Compounds (SVOC's) and Intermediate Volatile Organic Compounds (IVOC's) in a more comprehensive organic emission profile. For this analysis we will expand our discussion of VOC's to include all Non-Methane Organic Gasses (NMOG's). As can be seen in **Figure 5**, both highly loaded gas turbines and diesel engines without diesel particulate filters (DPF's) have similar, very low NMOG emissions. Tier IV diesel engines fitted with a diesel oxidation catalyst (DOC) or a diesel with a DPF perform much better than the gas turbines or standard diesel engines with respect to NMOG emissions.

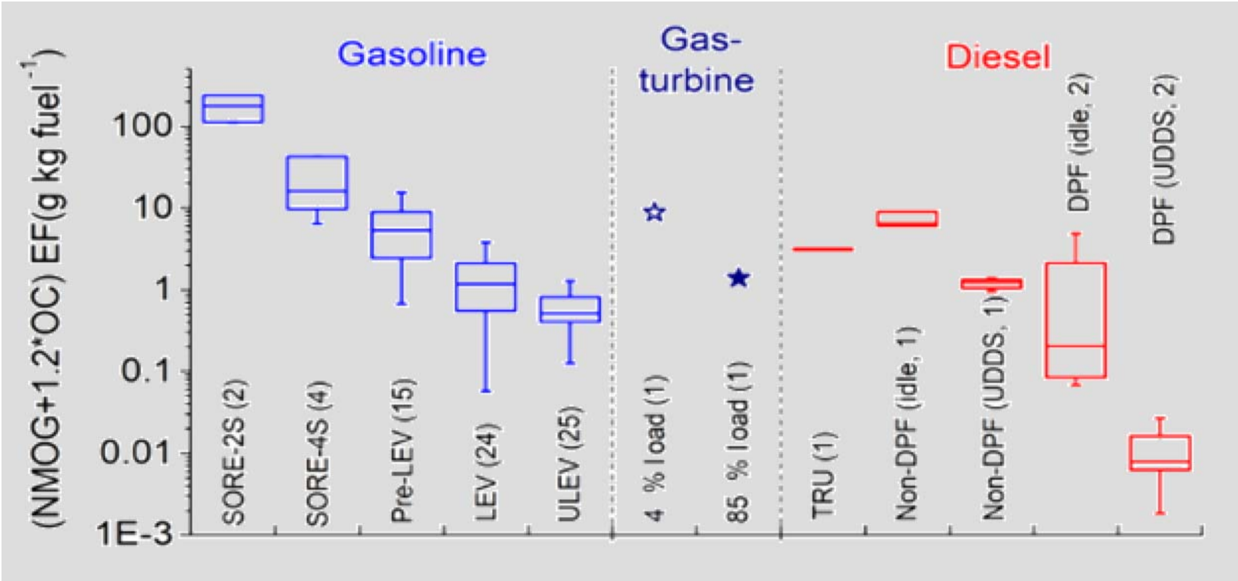

Figure 5 – VOC Emissions Source Q. Lu et al. (2017)

In the case studies presented, daily operational efficiencies of 45%, 58% and, 70% were assumed. For all the cases, all engines were left at idle during non-pumping time. There was an additional “Case 3” created to better load the turbines in the Permian. To do this, we assumed one 17 MW turbines and one 6 MW turbine which brought the load on each turbine up to 88%. This data point is shown for the 70% daily efficiency scenario. Under these conditions, **Figure 6**, **Figure 7**, and **Figure 8** below show the CO2e, CO and NOx emissions for the Permian. Similar plots can be seen for the Williston basin in the Appendix below.

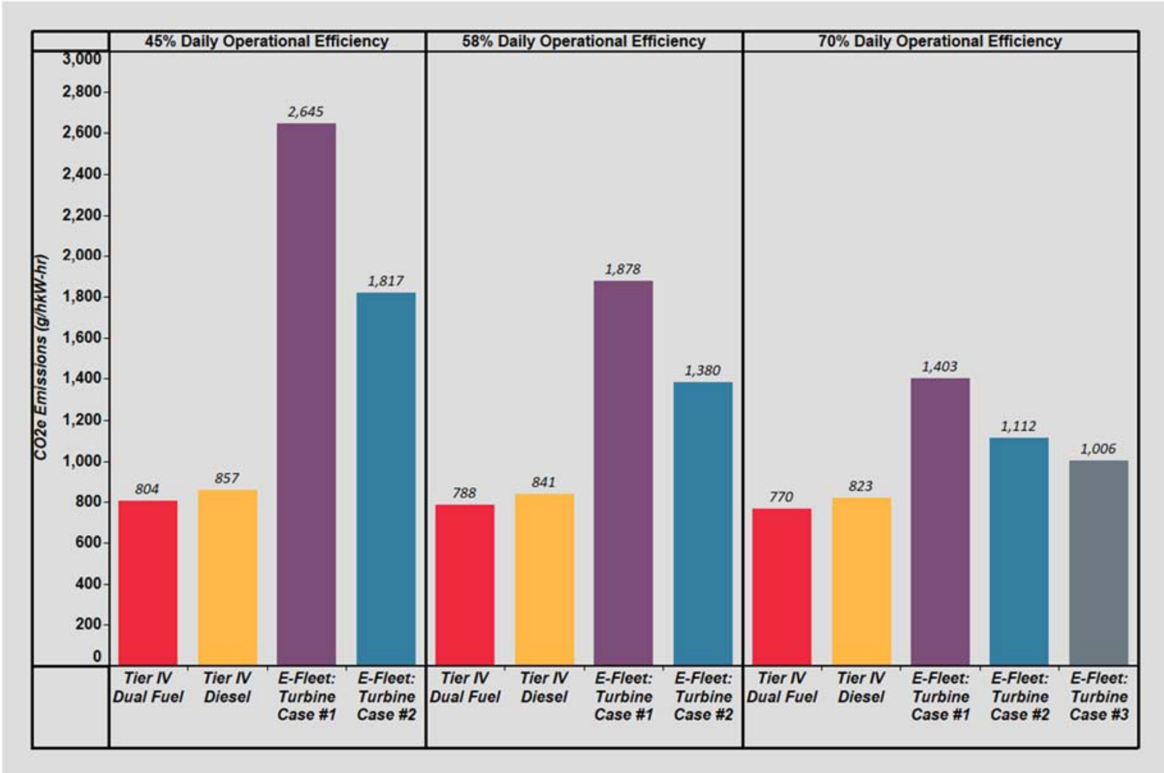

Figure 6 – CO2e Emissions in the Permian Basin at 67°F

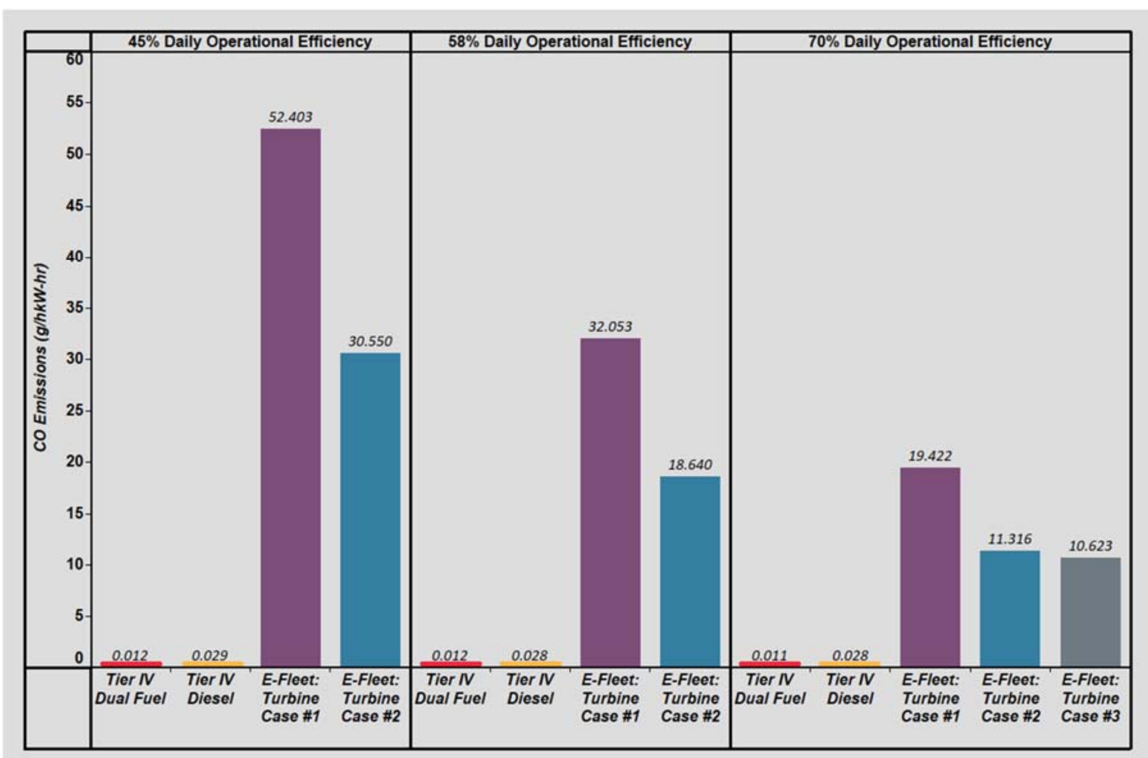

Figure 7 – CO Emissions in the Permian Basin at 67°F

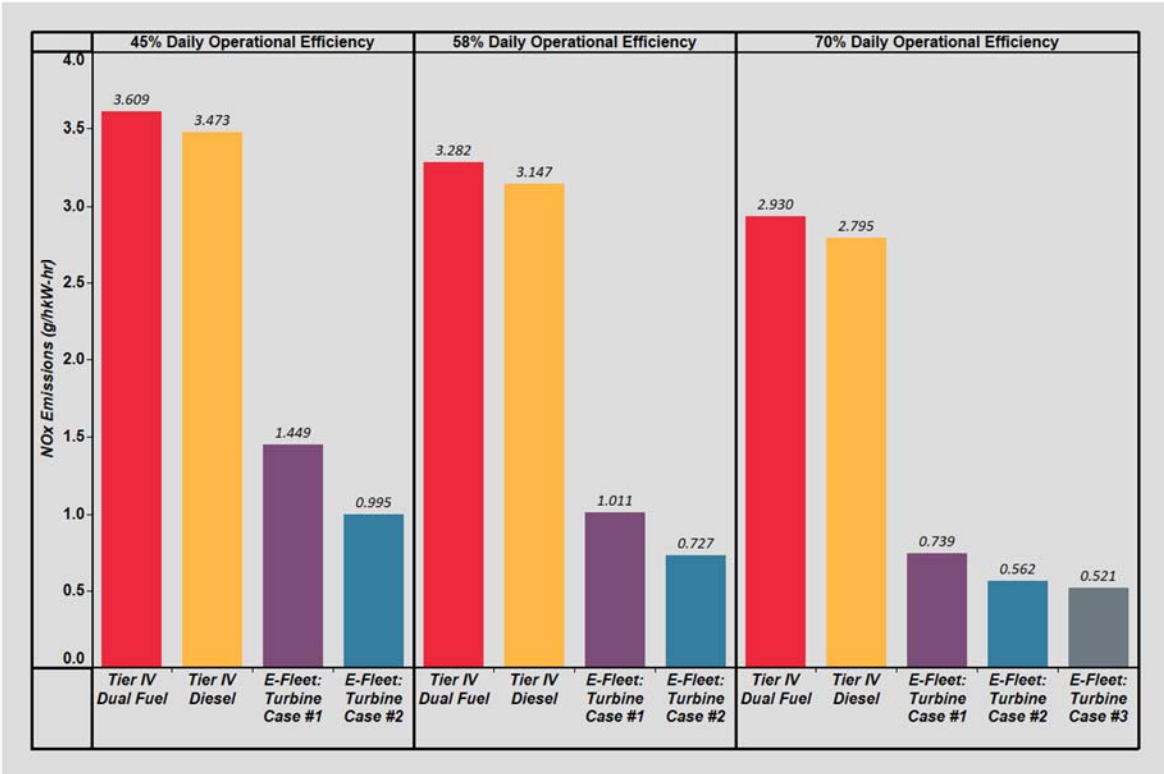

Figure 8 – NOx Emissions in the Permian Basin at 67°F

All e-fleet cases resulted in a significant increase in CO2e and CO emissions. Conversely turbine powered e-fleets demonstrated at least a 50% lower NOx emissions compared to the diesel/dual fuel fleets. The emissions are much higher for Turbine Case #1 than Turbine Case #2 and Turbine Case #3. This is because there are more units on location due to the lower power each unit can provide, which results in a compounded lowered efficiency. Lower efficiency, as discussed above, results in higher emissions. Turbine Case #3 results in further reduced emissions per unit of work done for e-fleets. This is a result of the turbines running at more favorable loads, which result in higher thermal efficiencies, as discussed above.

The same holds true with a reduction in daily operational efficiency , especially with turbines. This can be seen below in **Figure 9**, **Figure 10**, and **Figure 11,** which illustrate this effect for the Permian Case. As daily efficiency, or pump time per day, increases, the emissions per hour of work done decrease dramatically on all fronts for gas turbines. This is because when turbines are left idling, emissions of unburned hydrocarbons (Methane), CO, and NOx are increased significantly. Dual fuel fleets burn no gas and comparatively small amounts of fuel at idle. Thus they have consistently low Methane emissions at low loads, so the emissions curves seen below for dual fuel/diesel are practically flat compared to the turbine curves.

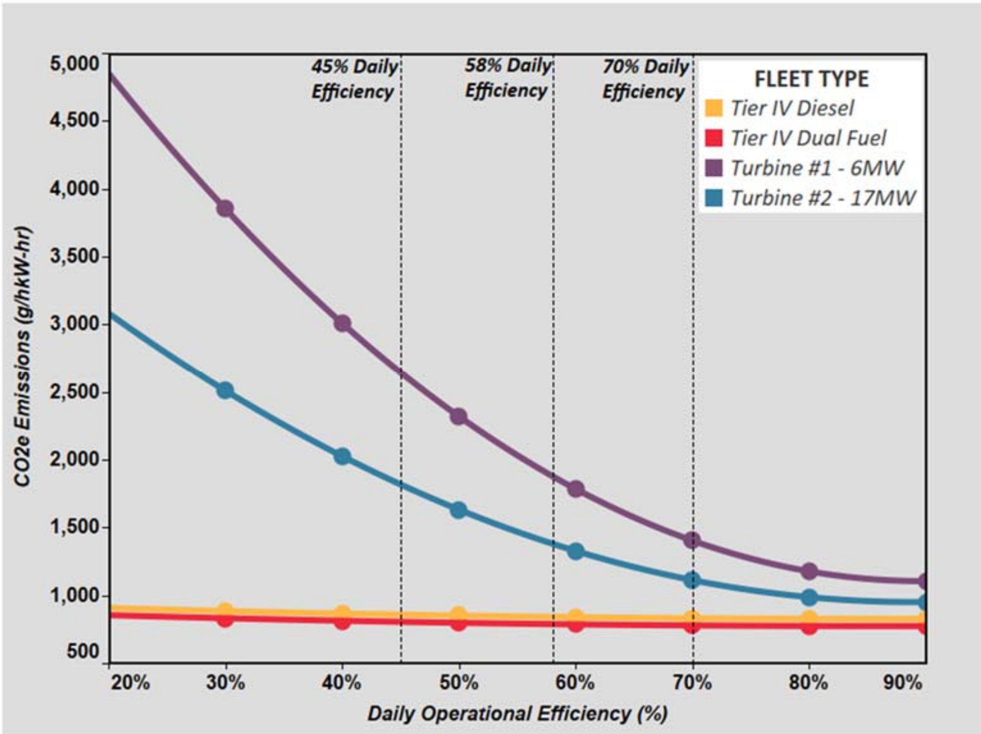

Figure 9 - CO2e Emissions vs. Daily Operational Efficiency for Permian Basin

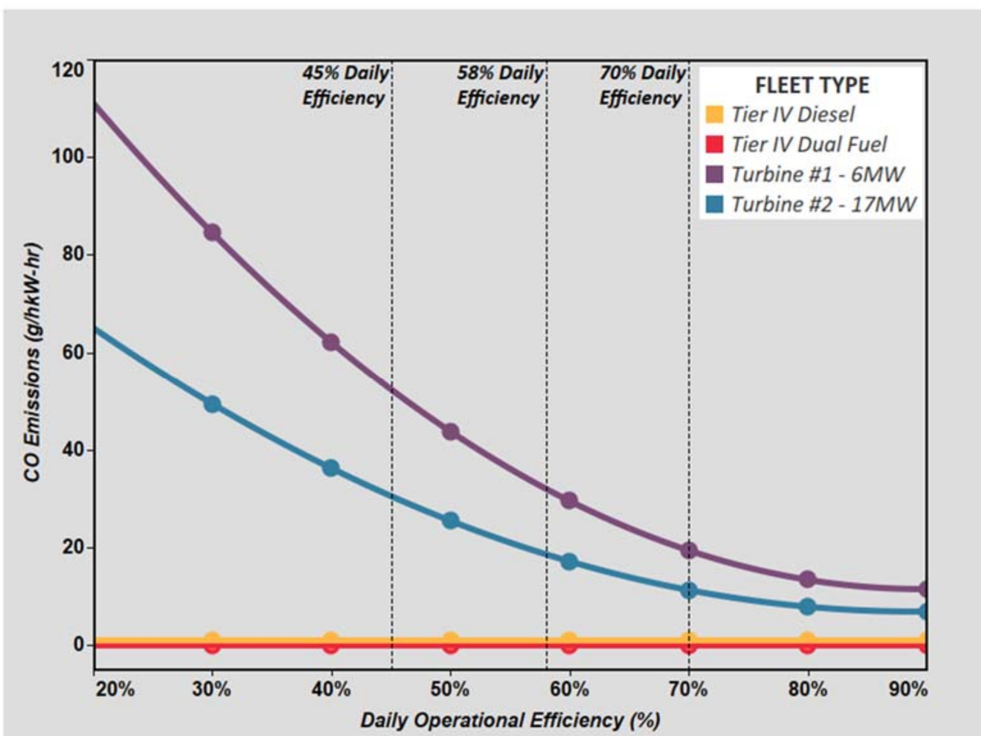

Figure 10 - CO Emissions vs. Daily Operational Efficiency for Permian Basin

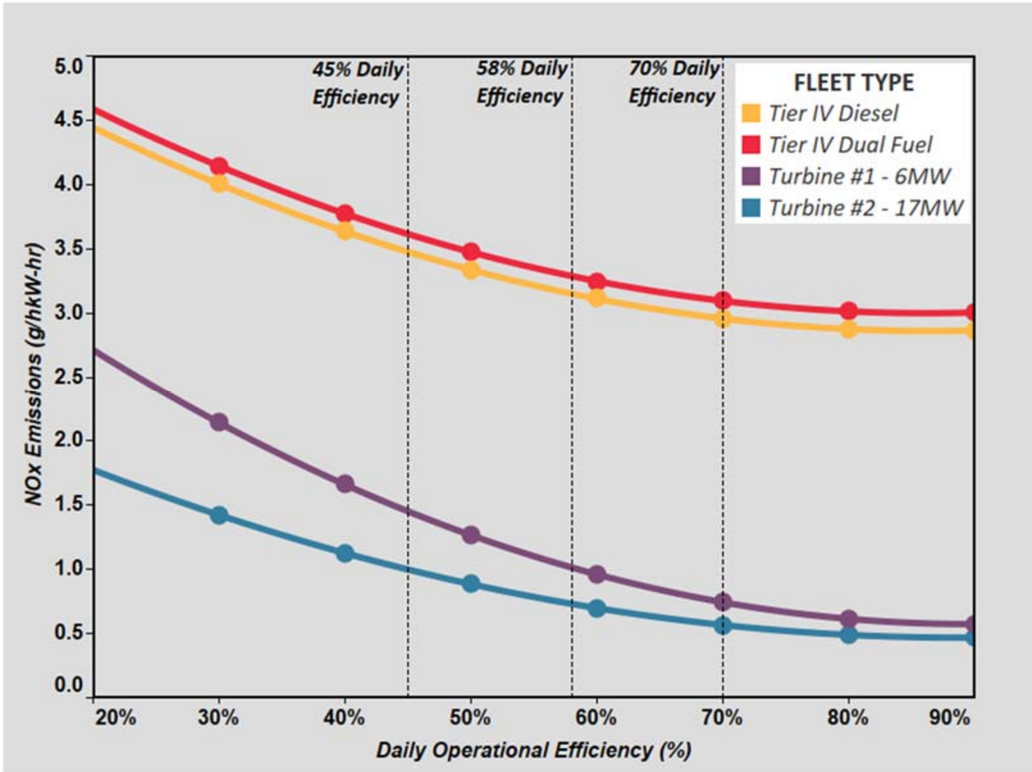

Figure 11 - NOx Emissions vs. Daily Operational Efficiency for Permian Basin

Figure 12 below shows the sensitivity of CO2e emissions based on different operational factors. While altitude and temperature have the smallest effect on emissions of turbines, operational efficiency and load profile have the largest effect. This is a notable finding as the two factors that have the greatest effect are also the most controllable factors. Optimizing these factors will greatly improve the emissions profiles for gas turbines. However, the total impact on emissions ends up being lower for dual fuel engines per the chart below.

Diesel/dual fuel engines have minimal sensitivities to changes in elevation or temperature. Similar to gas turbines, optimizing these factors will greatly improve the emissions profiles for dual fuel and diesel engines. These engines are more sensitive to load profile than operational efficiency. Operational efficiency does not have as large of an impact due to reduced emissions while idling.

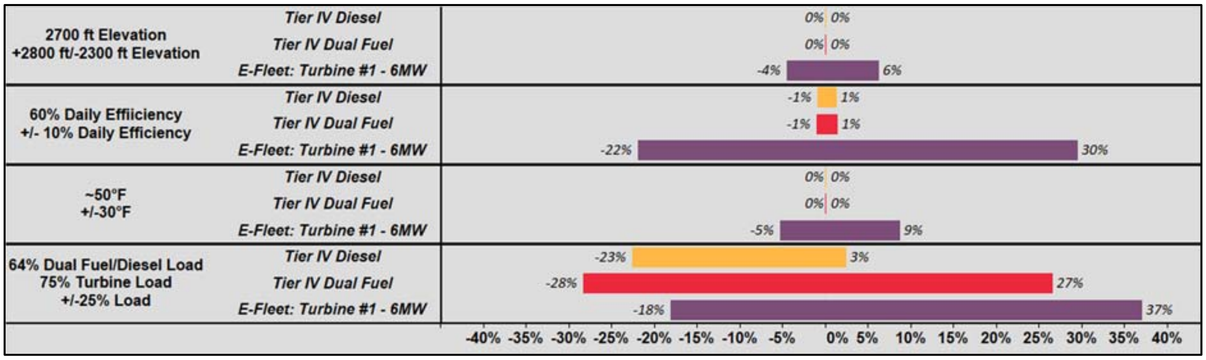

Figure 12 – CO2e Emissions Sensitivities Based on Operational Factors

Dual fuel and diesel fleets will have reduced CO2e and CO emissions compared to e-fleets. However, even though Tier IV diesel/dual fuel fleets have very low NOx emissions, turbines provide a significant additional reduction. In Case 3, the best-case e-fleet scenario, the e-fleet still produces ~23% more CO2e, 965 times more CO, but has an ~82% reduction in NOx emissions.

Simple Financial Analysis

This section of the report outlines some basic financial considerations for the various options. Specifically, estimates are provided for initial capital costs of each of the various solutions. Maintenance schedules and parts & labors cost assumptions were created and used to compare operating costs. Lastly fuel costs were evaluated based on assumptions for fuel pricing or natural gas supply channels. No calculations are provided with respect to payback metrics given the many variables that could differ from company to company.

Table 5 below shows the capital investment and operational expenses associated with Tier IV diesel, Tier IV dual fuel, and e-fleets. The CAPEX shown applies to the entire fleet, not just the power sources. The e-fleet requires the highest CAPEX, although it will vary based on turbine and fleet configuration. For this analysis, $40 MM was used for Tier IV diesel, $43MM was used for Tier IV dual fuel, and $63MM was used for e-fleets. A Tier IV diesel fleet requires the least CAPEX and a Tier IV dual fuel fleet falls in the middle.

Table 5 – Financial Analysis Table

	Tier IV Diesel	Tier IV Dual Fuel	E-Fleet
CAPEX ($MM)	$37 to $42	$39 to $44	$50 to $70
OPEX ($/pumping hour)	$1,740.38	$1,819.92	$1,616.41

Maintenance cost was estimated by summing the cumulative costs of parts & labor required to power each fleet system, including the pumps, for the life of the product then dividing by the cumulative pumping hours accrued on the fleet. Although the majority of maintenance expenses are associated with fluid end and consumables such as seats, valves, and packings, they would remain the same for diesel, dual fuel, and e-fleets. The table was also simplified by only showing the Permian case at 58% daily efficiency, as all other cases show the same relationship. The major difference for e-fleets is that the equipment which replaces engines and transmissions on e-fleets requires minimal routine maintenance followed by less frequent, but higher cost, rebuilds. This equipment includes the gas turbine, switchgear, transformers, VFD's and electric motors. For the most part, the maintenance on these pieces of equipment are visual inspections, cleaning, greasing and oil changes when needed. Gas turbines also require an air filter replacement bi-annually. Although diesel/dual fuel fleets also require similar maintenance, it is more frequent and extensive. Therefore, we believe e-fleets will have roughly an 11% reduction in maintenance costs over diesel/dual fuel. If a 4,000-pumping hour year is assumed, the e-fleet would benefit from about $800,000 worth of maintenance savings per year compared to the diesel/dual fuel fleet. There is an active debate in the area of maintenance savings but if we assume an additional

$20MM investment for e-fleets, an annual maintenance saving of $3.25MM would be required for 10 years at a discount rate of 10% to achieve a positive NPV.

Most of the e-fleet savings come in the form of fuel cost. There are three potential types of natural gas which can be utilized on a frac location: compressed natural gas (CNG), liquified natural gas (LNG), and field gas. The unit of measurement used to define natural gas is diesel gallons equivalent (DGE) in order to easily compare natural gas data to diesel data. **Figure 13** and **Figure 14** below show the fuel cost per stage for a 58% daily efficiency in the Permian and Bakken, respectively. For the dual fuel cases, the cost includes the respective natural gas and diesel expenses. The prices assumed were: $2.85 for diesel, $1.60/DGE for CNG, and $1.36/DGE for LNG. All assumed prices include an estimated transportation cost. For field gas, a miscellaneous price, which includes transportation, of $0.30/DGE was assumed along with the daily cost of $3,000/day for the location field gas treatment equipment. For the Permian plot below, the price per stage for field gas was calculated using the following method:

$$Diesel\ \$/Stage = 2206.29\,\frac{gal}{stage} \times \frac{\$2.85}{gal} = \$6{,}288 \qquad \textbf{\textit{Equation 2}}$$

$$Dual\ Fuel\ \$/Stage = \left(603\,\frac{gal}{stage} \times \frac{\$2.85}{gal}\right) + \left(\left(\frac{\$0.30}{DGE} \times 1601.55\,\frac{DGE}{stage}\right) + \left(\frac{\$3000}{day} \times \frac{day}{7.82\ stage}\right)\right) = \$2{,}581 \qquad \textbf{\textit{Equation 3}}$$

$$6MW\ Turbine\ Fuel\ \$/Stage = \left(\frac{\$0.30}{DGE} \times 3303\,\frac{DGE}{stage}\right) + \left(\frac{\$3000}{day} \times \frac{day}{7.82\ stage}\right) = \$1{,}375 \qquad \textbf{\textit{Equation 4}}$$

$$17MW\ Turbine\ Fuel\ \$/Stage = \left(\frac{\$0.30}{DGE} \times 3411\,\frac{DGE}{stage}\right) + \left(\frac{\$3000}{day} \times \frac{day}{7.82\ stage}\right) = \$1{,}407 \qquad \textbf{\textit{Equation 5}}$$

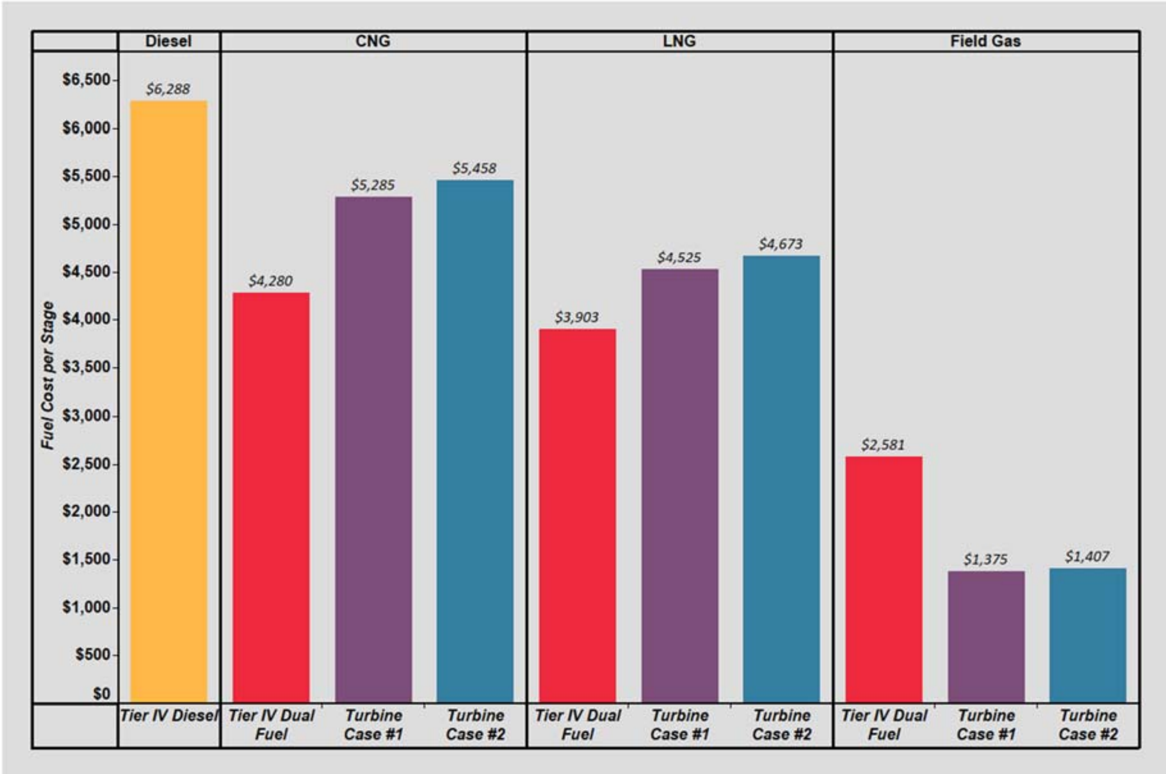

Figure 13 – Fuel Cost per Stage at 58% Daily Efficiency in the Permian Basin

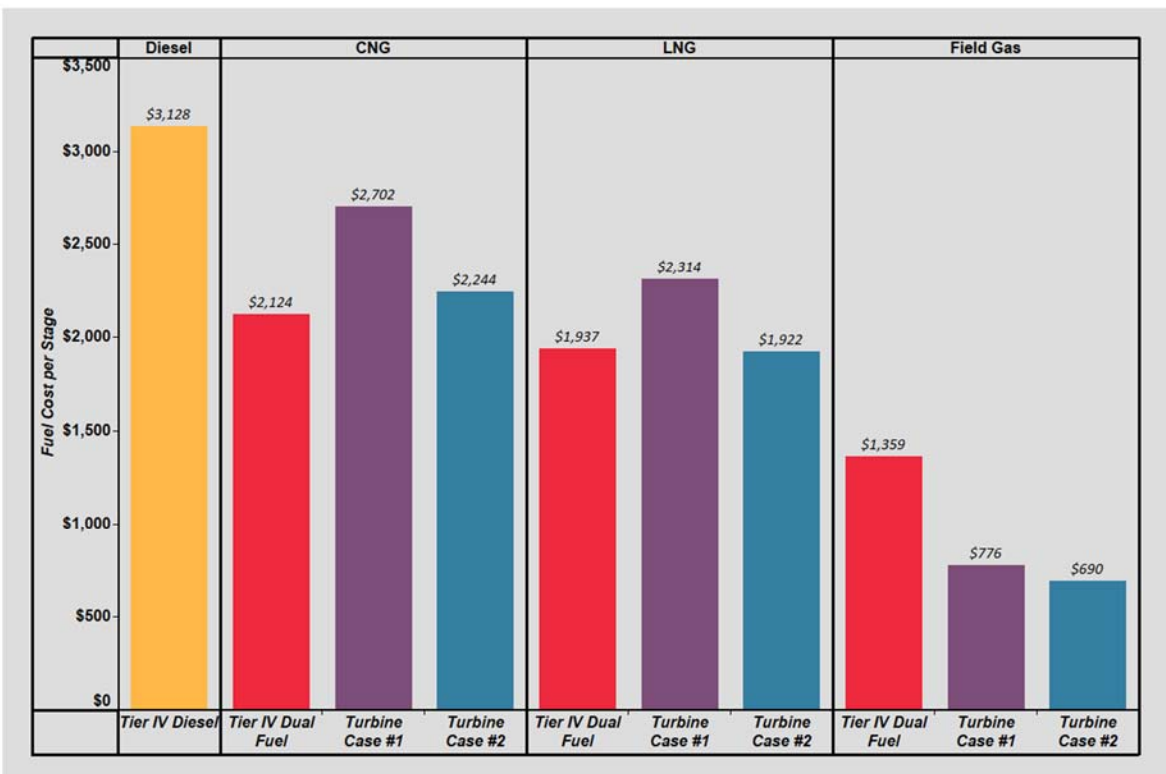

Figure 14 – Fuel Cost per Stage at 58% Daily Efficiency in the Williston Basin

Dual fuel and e-fleets have reduced fuel costs per stage compared to diesel fleets. There are large variations in the price and availability of LNG and CNG within each basin, affecting the ultimate reduction. In the Bakken, the lowest cost per stage resulted from the 17 MW turbine configuration when using only field gas. In the Permian, the 6 MW option is the cheapest option when utilizing field gas. However, as with the emissions, the largest fuel consumption savings result from higher daily efficiencies. This concept is reflected in **Figure 15** below. As the daily efficiency increases, fuel consumption per hour of work done decreases significantly, especially in the turbine cases due to idling consumption.

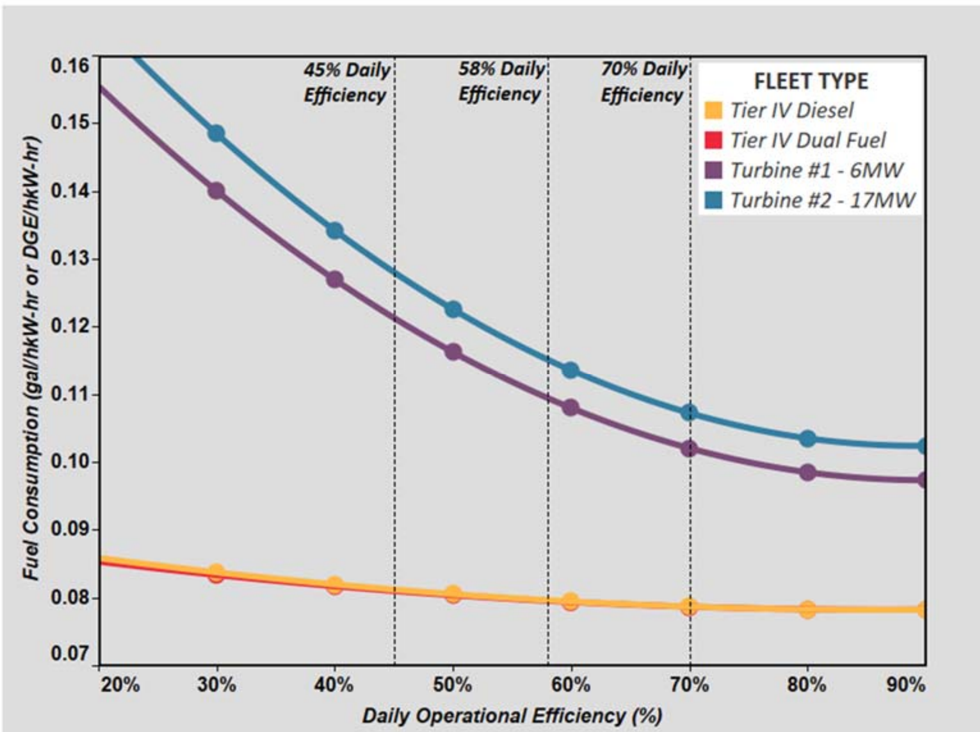

Figure 15 – Permian Case: Fuel Consumption vs. Daily Operational Efficiency for Diesel, Dual Fuel & E-Fleets

As seen in **Figure 15**, gas turbines require almost double the fuel compared to dual fuel fleets. This benefit is offset by the fact that dual fuel fleets require diesel as well as natural gas. In the end the higher fuel consumption of the turbines offset the higher cost of the diesel component of the dual fuel fleet and the two had very similar fuel costs when burning CNG or LNG.

In conclusion, e-fleets have larger initial investment than diesel/dual fuel fleets. However, the cost to operate e-fleets and the fuel costs (compared to diesel) are smaller if and when operating efficiently. Depending on the contract between the service company and the operator, both companies could have potential savings. As far as an investment from the service company's perspective, the dual fuel fleet is the generally better option compared to the e-fleet. Dual fuel has a lower initial CAPEX requirement which outweighs the e-fleets' reduced maintenance costs.

Operational Considerations

Redundancies

With traditional diesel fleets, it is common practice to have additional horsepower on location so that if maintenance is needed mid-stage on a pump, another pump can make up for the lost rate. This operating theory should also be followed in the dual fuel and e-fleet landscape. With dual fuel, the infrastructure and maintenance patterns of the fleets will be almost identical to diesel fleets. Fuel redundancy is also a consideration. If there is an interruption in the gas supply to the dual fuel engine it seamlessly switches to 100% diesel. The dual fuel pumps carry their own backup fuel supply.

One of the purported attributes of e-fleets is that the pumps will need less maintenance due to reduced vibrations. Although this may have a small effect on maintenance patterns, it is not likely to result in a noticeable difference. The primary drivers of pump maintenance on location are treating pressure, proppant concentration, and proppant type. For this reason, we assumed that the same amount of reserve horsepower be available for all types of fleets.

Although the smaller, multiple turbine set up has increased emissions and costs, operationally they provide the desired redundancy. If one turbine goes down, there should be enough power to flush the well. However, if there is one single large turbine powering the fleet, the risk of screening out increases. If the single turbine fails during a stage, there is no other source of power to flush the well, resulting in a screen out and wellbore full of sand. For this reason, Turbine Case #1 makes the most sense operationally. One potential solution to the risk involved with having a single turbine powering the fleet is to have an extra, smaller turbine on location which can be used to flush the well in the case of a turbine failure. Another solution could be to have diesel/dual fuel pumps inline that can be used for a short period of time. In the case that the pump down equipment is still diesel/dual fuel, pump down could also be used to flush the well. Both options come with an incremental capital cost, although the turbine would be much higher than a dual fuel/diesel solution. Backup fuel supply for turbines require additional tanks of CNG or LNG and the associated equipment. There is an additional cost associated with having this equipment on location.

Fuel Considerations

Field gas has been at the forefront of the push towards e-fleets. There are considerable cost savings if gas turbines can be run entirely on field gas. Field gas is low cost and abundant in most basins and in many cases, it will be flared if it is not used in this application. However, in order to use field gas to power gas turbines or dual fuel fleets, it must first be treated. **Figure 16** shows the general flow path of field gas from wellhead to flare or frac site.

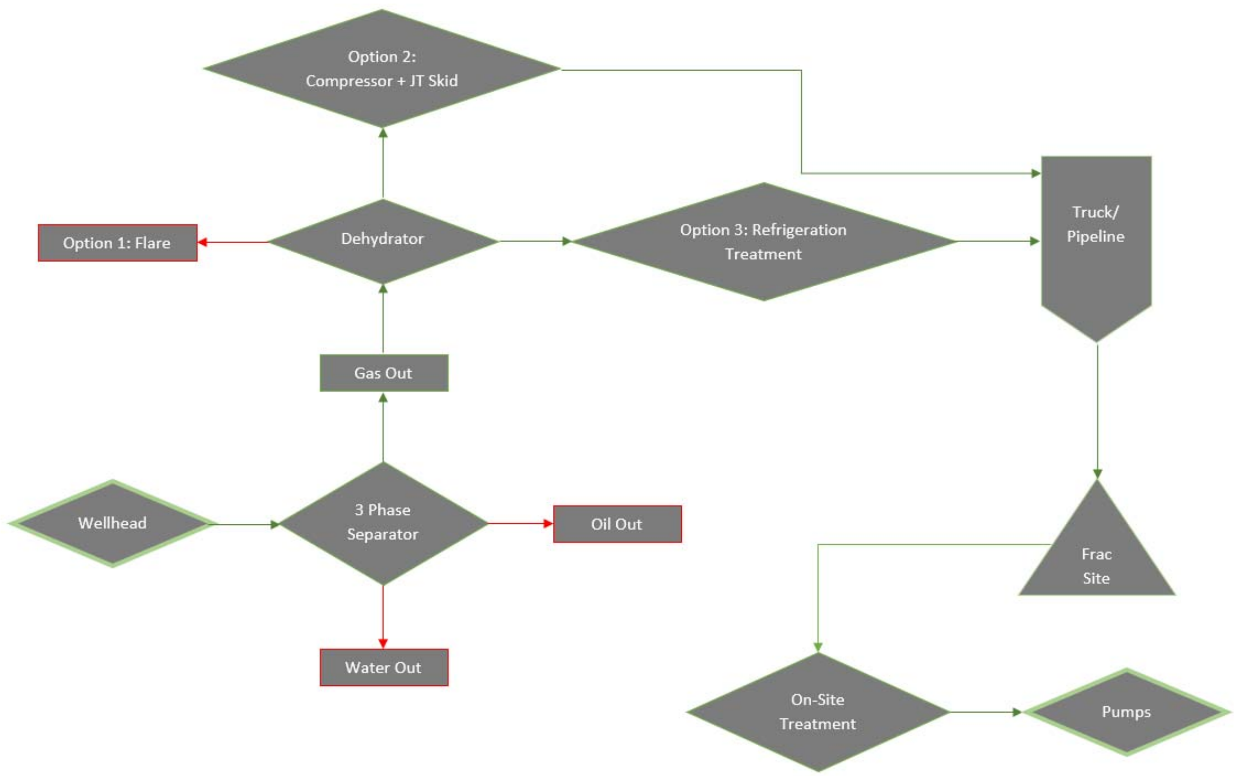

Figure 16 – Potential Field Gas Flow Path

In order to use field gas, the necessary infrastructure must first be put into place to process the gas. The CAPEX associated with this infrastructure can vary based on the artificial lift practices in place. Turbines generally require the gas to be compressed to around 500 psi. Dual fuel engines require a lower feed pressure of about 100 psi. If gas lift is being used nearby it will be relatively inexpensive and simple to begin using field gas to power completions equipment. Gas lift requires that the gas be compressed and delivered in high pressure lines. If gas lift is not being utilized, high pressure gas lines and compressors must be purchased. The cost of these can vary, but in general a high-pressure gas line will cost around \$25,000 per mile and typical compression stations cost around \$200,000 in CAPEX and \$10,000/year in auxiliary operation costs. There may be further processing equipment on location in order to remove liquids, remove H2S and regulate temperature and pressure. This will typically cost around $3,000 to $6,000 per day.

The main hurdle associated with field gas is keeping the quality of gas up to specifications. In general, decreased fuel quality will result in higher emissions and lower thermal efficiencies. In some cases, the fuel quality may cause emissions to drop below the EPA and/or governments' standards. Not to mention the additional complications that arise with anomalies such as Hydrogen Sulfide in field gas, which causes damage to the engines and turbines. **Table 6** below shows the CO2 emissions percent change for gas turbines running at 100% load in the Permian at 70.3°F based on natural gas quality. As depicted, fuel quality will have a massive effect on the emissions of turbines. For further discussion on Methane Number, please see appendix.

Table 6 – CO2 Emissions Based on Fuel Quality

Fuel Type	Methane Number	LHV (BTU/scf)	6MW Turbine - CO2 Emissions Percent Change	17MW Turbine - CO2 Emissions Percent Change
Field Gas Sample 1	<46.8	1,509	9%	7%
Field Gas Sample 2	<46.8	1,421	6%	6%
Field Gas Sample 3	48	1,290	6%	6%
Field Gas Sample 4	50	1,266	9%	9%
Field Gas Sample 5	65	1,123	6%	6%
Field Gas Sample 6	56	1,197	5%	5%
LNG Sample	72	1,039	1%	1%
CNG Sample	74	1,104	3%	3%
San Diego Pipeline Quality	82	939	0%	0%

In addition to impacting the emissions of a turbine, fuel quality will affect the operational reliability of a turbine. When turbines are burning clean, dry gas, they are wonderfully reliable. Wet gas, on the other hand, will present liquid slugs into the system which can damage the gas compressor or turbine itself. There have been reported cases of substantial downtime caused by poor gas quality. Therefore, gas treatment is necessary in order to condition the gas and drop out as much liquid as possible.

Fuel quality will not affect dual fuel engines in the same way. A decrease in fuel quality in this case results in potential decreased diesel displacement, not a change in emissions. For example, decreasing the Methane Number by 20 for a Tier IV dual fuel engine will result in an averaged 19% reduction in diesel displacement. This means that 19% less natural gas is being used. This measure was taken across multiple engine speeds and loads. The change in diesel displacement with changing fuel quality also depends heavily on these factors.

When diesel displacement is decreased, the emissions caused by the additional diesel will be equivalent, and in some cases better, than those caused by a low-quality natural gas. With a greater amount of diesel being pumped in relation to the lower quality gas, the emissions remain virtually the same. If the Methane Number changes from 82MN to 57MN when operating at an engine load of 50% and an engine speed of 1600 rpm, the CO2 emissions will increase from 599.7 g/hkW-hr to 600.8 g/hkW-hr. Under the same conditions at an engine speed of 1700 rpm, CO2 emissions will decrease from 660.9 g/hkW-hr to 634.0 g/hkW-hr. While the diesel displacement does not significantly affect the emissions, it will increase the fuel costs, as diesel is more expensive than natural gas.

Typically, CNG or LNG must be on location as a backup in the case that field gas cannot be pumped because of lowered quality or other operational factors. LNG will typically have a Methane Number around ~72M while CNG will typically have a Methane Number around ~74MN. In most basins LNG and CNG will be readily available.

Figure 17 shows a general availability map for CNG in the US and **Figure 18** shows a general availability map for LNG in the US.

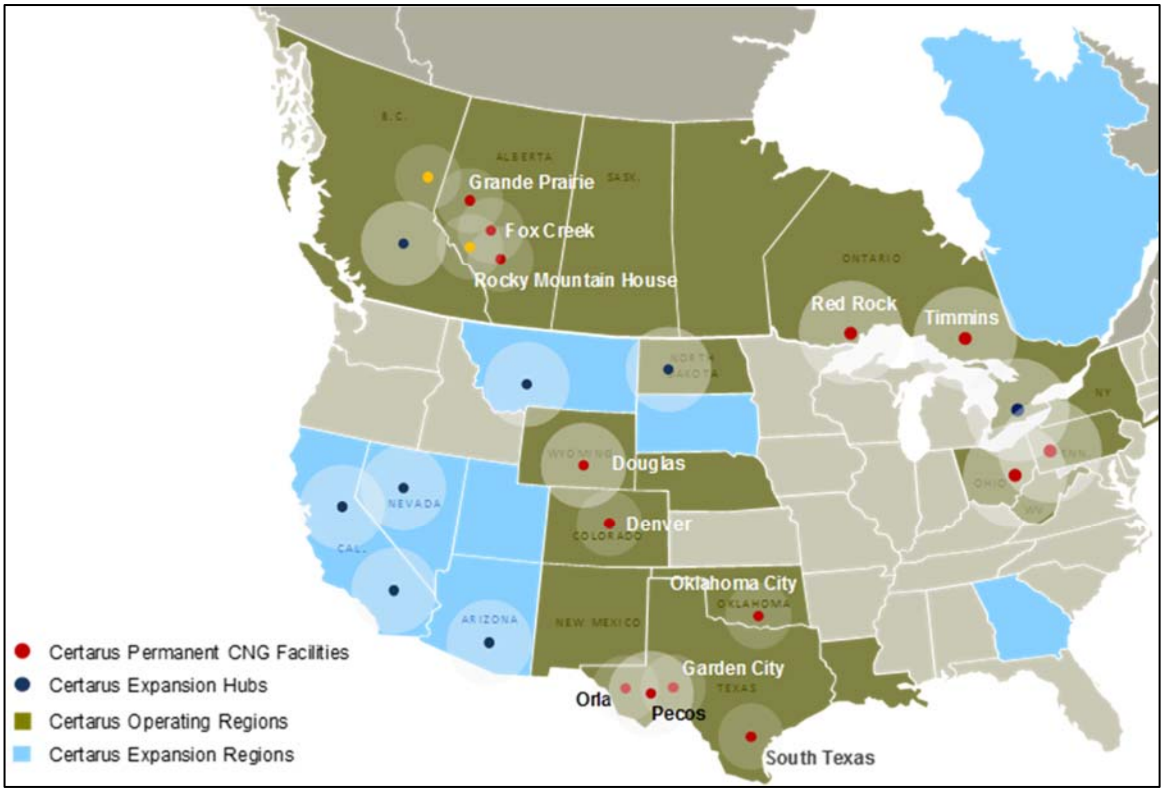

Figure 17 – CNG Availability in the US from Certarus

Figure 18 – LNG Availability in the US

Although there are some areas of operation which are not covered in the above maps, CNG and/or LNG can be trucked to most locations from the current infrastructure. If the demand is high enough in a potential area of operation currently lacking infrastructure, a new distribution station could be constructed in about 6 months.

In general, it is easier to transport and store LNG given its higher density in liquid form. A transport can carry about three times as much LNG as CNG, which means that LNG requires fewer loads. For an average frac job, approximately 4-6 trailers worth of CNG would cover a day of operations while LNG would need 1-2 trailers.

Manpower Considerations

There are several key differences in staffing requirements for a conventional fleet powered by a reciprocating engine versus an e-fleet using a gas turbine. While pump maintenance, sand, chemicals and job execution duties remain unchanged (as does the number of people required), specific maintenance expertise is different. The traditional role of a diesel engine mechanic is replaced by different specialized knowledge, specifically maintenance and operation of a gas turbine and maintenance and operation of medium and high voltage electrical equipment. This means a transition from a traditional fleet to an e-fleet when considering infrastructure and training required within a service company. On the other hand, a dual fuel fleet is virtually identical to a traditional diesel fleet and, as a result, the transition from diesel to dual fuel is minimal.

Operational Footprint

Because of the power density of an electric motor, additional options are available for pump design. These include locating 2 pumps on a single trailer, driven by a single electric motor, or using a single higher horsepower pump, again driven by a single motor. This would reduce the footprint required by the pumps on location because only half of the pump trailers would be needed. The reduction in space used by the pumps is then offset by the need for the turbine(s), conditioning skids, switchgears, etc. As a result, an e-fleet has a similar footprint to a traditional frac fleet.

There is a method, however, that can be employed to effectively reduce the footprint for e-fleets on the actual wellsite. Utilizing remote power generation would remove the turbine(s) and gas processing/storage equipment from the location. From a centralized location, it would be possible to run the power to multiple locations. It should be noted that this solution involves additional capital cost and complexity to install the necessary localized grid.

Summary/Conclusions

As with all forms of energy, there is a trade off in optimizing the "Three E's" when switching between energy sources. In the case of dual fuel versus e-fleets, the best case will be distinguished by optimizing equipment and operational efficiencies. In general e-fleets will result in lowered NOx emissions while dual fuel will have decreased CO2e and CO emissions, comparatively. Additionally, although e-fleets have a higher initial investment compared to dual fuel fleets, they have cost savings based on maintenance and fuel practices.

Dual fuel fleets will be easy to implement, as they are very similar to the existing infrastructure of diesel fleets. The largest hurdle will be, if choosing to use field gas with e-fleets, keeping the quality of gas above the Methane Number required to keep emissions within standards. For dual fuel fleets, the fuel quality must be kept above the Methane Number required for the engines, as discussed above. E-fleets will have additional hurdles in implementation, as they represent a more significant change in equipment.

Overall, both technologies are options which can be utilized to meet the criteria of a pressure pumping fleet. It is up to both the service company and operator to decide their efficiency, emissions, and economic priorities to determine which technology to capitalize on. In either case, maximizing efficiencies should be at the forefront of this progression in order to further reduce emissions and costs.

Author Bios

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Roy is the Director of Research and Development for Liberty Oilfield Services. He has an extensive project background in resource extraction in mining and served as Director of Engineering for Amcol International and CEO of Cronimet Chrome Mining South Africa prior to joining Liberty.

Roy received an undergraduate degree in Mechanical Engineering Technology from Montana State University and a Masters in Operations Management from Syracuse University. He has spent the majority of his career working with heavy equipment. He also has extensive power distribution experience and was senior project engineer for the installation of a new 69kV/13.8KV system in Montana and managed a 2MW photovoltaic solar installation in Africa.

Chris Wright

Chris is the CEO and Chairman of Liberty Oilfield Services and Executive Chairman of Liberty Resources. He has been a career energy entrepreneur.

Chris received an undergraduate degree in Mechanical Engineering from MIT and then pursued graduate studies in Electrical Engineering at U.C. Berkeley and MIT in the area of power electronics and semiconductor device physics. He also worked briefly on fusion energy at MIT and solar energy at Berkeley. Chris has authored over 60 technical papers on a wide variety of energy technologies, most significantly in the area of hydraulic fracturing surrounding the start of shale revolution in the late 1990's.

Madison Hollaway

Madison is a Field Engineer II at Liberty Oilfield Services. She has worked in multiple shale plays throughout the US, including the Williston and DJ Basins.

Madison received her undergraduate degree in Petroleum Engineering from Texas A&M University, where she graduated Cum Laude.

Appendix

Additional Natural Gas Discussion

Methane number is a measure used to determine the knock resistance of fuel. The knock of a fuel is basically when the fuel burns unevenly due to the air and fuel mixture. This is a function of fuel composition, with a specific emphasis on Methane, ethane, propane, and butane. Pure Methane has an index value of 100, which indicates that it is highly resistant to knock. On the other hand, Hydrogen has a value of 0, indicating that is has no resistance to knock. The Methane Number is an indication of the equivalent Methane/Hydrogen mixture of that fuel. For example, if a gas has a Methane Number of 80, burning that gas would be like burning a mixture of 80% Methane and 20% Hydrogen. A link to a Methane Number calculator is listed below:

Methane Number Calculator

As discussed above, as Methane Number decreases, emissions will increase. This is very dependent on the composition of the fuel as well. If there are two 80MN fuels, one with 2% hexane+ and one with 5% hexane+, the one with the higher percentage of hexanes will result in higher emissions. Overall, as the hydrocarbon chains get longer, the emissions will increase.

Definitions

- **Simple Cycle Turbines** – the turbines have no method of waste heat recovery. In this case, the steam which results from burning the gas is not utilized. This is currently the only option for frac applications.
- **Combined Cycle Turbines –** the steam which is created from burning the gas is rerouted into a steam turbine. This increases the efficiency and power of the system. For the time being, the equipment required for this technology is too large to maneuver to a frac location.
- **DGE –** diesel gallon equivalent. This unit is utilized to easily compare natural gas volumes to diesel volumes. The conversion factor from standard cubic feet (scf) to diesel gallon equivalent is: 1 DGE = 139.3 scf.
- **Dual Fuel Engine –** a dual fuel engine utilized a mixture diesel and natural gas when a load is applied.
- **Diesel Displacement –** the ratio of natural gas to diesel which is being used to power the engine. For example, if diesel displacement is 75%, a blend of 75% natural gas and 25% diesel is being used. During operation, the dynamic gas blending system continuously monitors the engine and

combustion for abnormal and uncontrolled combustion cause by anomalies and general reduced quality in the natural gas. When an abnormality is detected, diesel displacement will be decreased in order to return the combustion to normal operating conditions.

- **Emissions**
  - **CO2e –** Carbon Dioxide Equivalent. This includes all greenhouse gases. Each gas has an equivalent global warming potential (GWP) to Carbon Dioxide. For example, Methane will contribute 25x more to global warming that Carbon Dioxide. All components of CO2e and their associated GWP can be seen below. For this analysis only CO2 and CH4 were considered while calculating CO2e emissions. Both turbines and diesel/dual fuel engines generate trace amounts of N2O, but they are not a significant source of greenhouse gases.

Table 7 – CO2 Equivalent GWP

Greenhouse Gas	Global Warming Potential (GWP)
Carbon Dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Hydrofluorocarbons (HFCs)	124 - 14,800
Perfluorocarbons (PFCs)	7,390 - 12,200
Sulfur Hexafluoride (SF_6)	22,800
Nitrogen Trifluoride (NF_3)[3]	17,200

  - **NOx –** encompasses both Nitrogen Oxide (NO) and Nitrogen Dioxide (NO2). These emissions are one of main constituents of smog. When combined with unburned hydrocarbons in the atmosphere, smog will appear.
  - **CO** – Carbon Monoxide. When animals and humans are exposed to extremely concentrated amounts of CO, it can be extremely toxic.
- **Greenhouse Gases –** these include Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF6), and Nitrogen Trifluoride (NF3). These seven gases contribute to global warming. Neither NOx nor CO are considered greenhouse gases.
- **Thermal Efficiency –** energy in versus energy out. In this case, energy in is the energy provided by the fuel, measured by the lower heating value. Energy out is the power produced by the turbine/pump.

Further Emissions Data

Below are the CO2e, CO, and NOx emissions for the Williston, **Figure 19** to **Figure 21**.

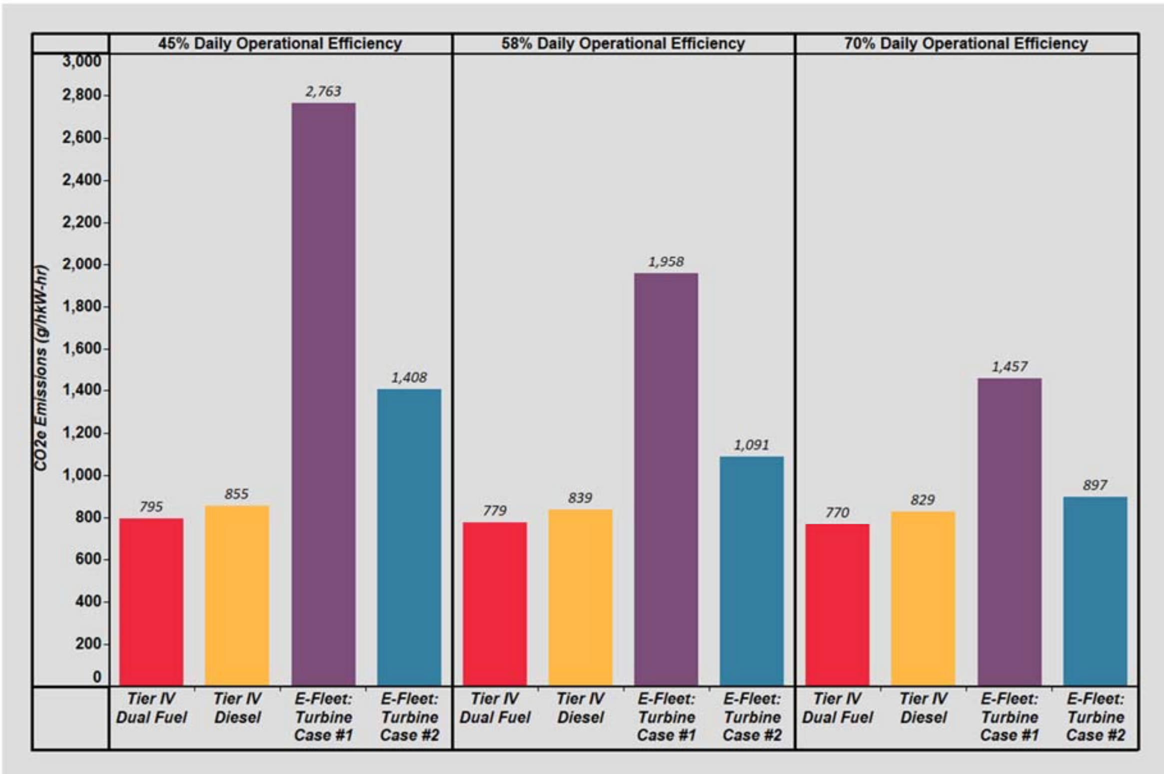

Figure 19 – Williston CO2e Emissions at 67.3°F

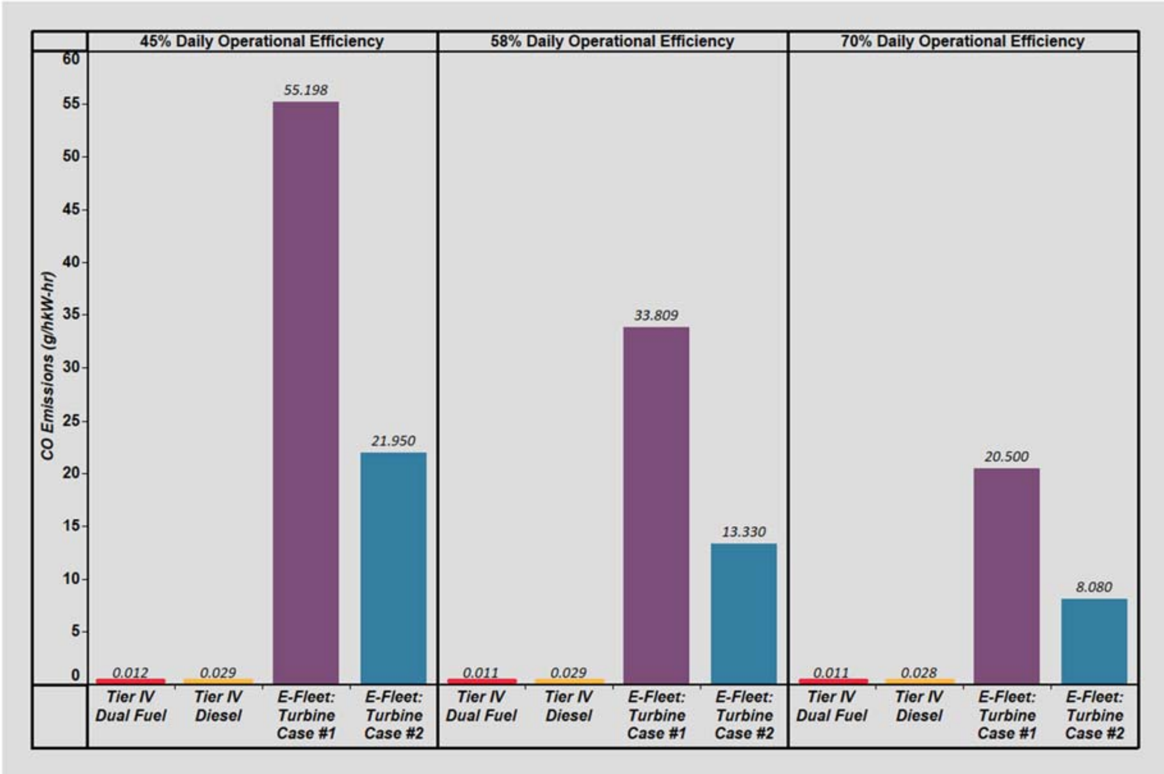

Figure 20 – Williston CO Emissions at 67.3°F

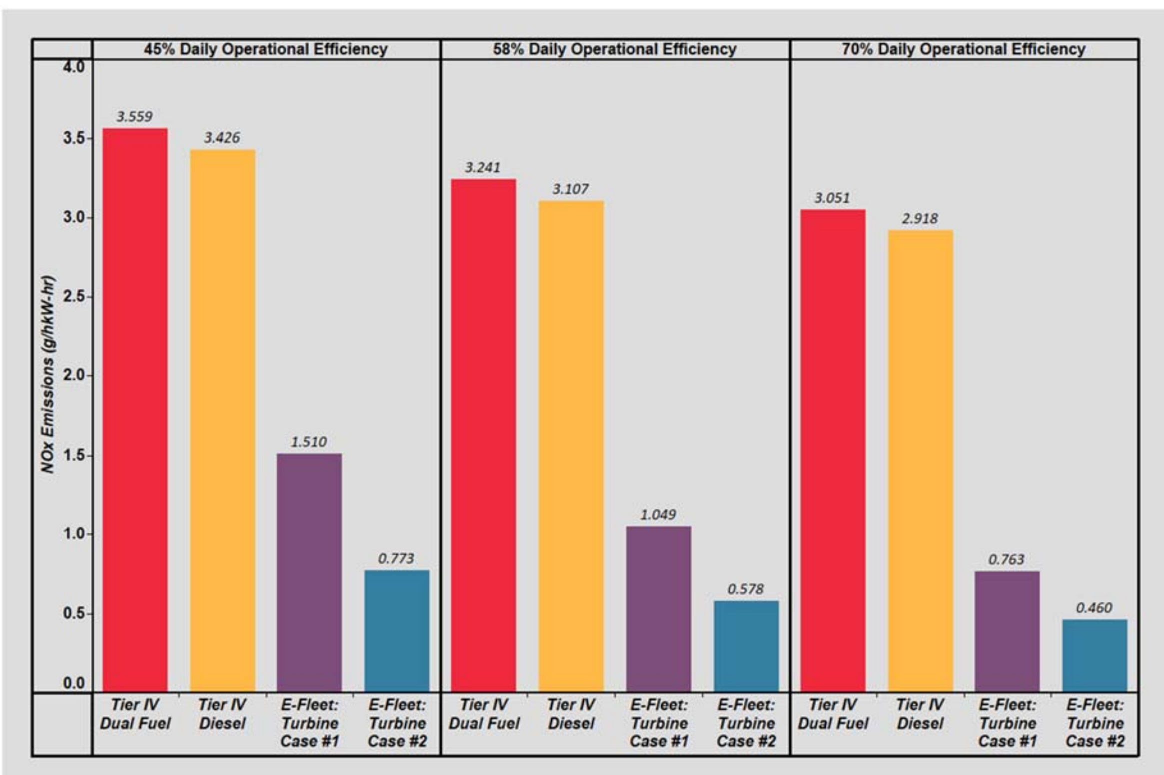

Figure 21 – Williston NOx Emissions at 67.3°F

Fuel Costs per Stage by Basin

Table 8 and **Table 9** below show the estimated fuel costs per stage for the Permian and Williston Basins, respectively, at different daily efficiencies.

Table 8 – Cost per Stage in Fuel for Permian Basin

Fuel Type	Fleet Type	45% Daily Efficiency	58% Daily Efficiency	70% Daily Efficiency
Diesel	Tier IV Diesel	$6,411.73	$6,287.91	$6,214.44
CNG	Tier IV Dual Fuel	$4,394.74	$4,279.78	$4,211.55
	Turbine Case #1	$6,006.15	$5,285.02	$4,854.42
	Turbine Case #2	$6,193.47	$5,457.54	$5,018.06
LNG	Tier IV Dual Fuel	$4,018.39	$3,903.41	$3,835.19
	Turbine Case #1	$5,142.77	$4,525.30	$4,156.60
	Turbine Case #2	$5,303.16	$4,673.02	$4,296.71
Field Gas	Tier IV Dual Fuel	$2,807.17	$2,581.38	$2,447.39
	Turbine Case #1	$1,620.39	$1,374.57	$1,228.00
	Turbine Case #2	$1,655.51	$1,406.92	$1,258.68

Table 9– Cost per Stage in Fuel for Williston Basin

Fuel Type	Fleet Type	45% Daily Efficiency	58% Daily Efficiency	70% Daily Efficiency
Diesel	Tier IV Diesel	$3,190.24	$3,128.14	$3,091.28
CNG	Tier IV Dual Fuel	$2,180.17	$2,124.27	$2,091.11
	Turbine Case #1	$3,084.28	$2,702.42	$2,477.37
	Turbine Case #2	$2,505.03	$2,244.46	$2,091.11
LNG	Tier IV Dual Fuel	$1,993.20	$1,937.31	$1,904.14
	Turbine Case #1	$2,640.91	$2,313.95	$2,121.25
	Turbine Case #2	$2,144.93	$1,921.82	$1,790.52
Field Gas	Tier IV Dual Fuel	$1,493.12	$1,359.40	$1,280.05
	Turbine Case #1	$925.52	$776.00	$687.72
	Turbine Case #2	$816.92	$690.14	$615.30